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Jet-breaks in the X-ray Light-Curves of Swift GRB Afterglows

A. Panaitescu
Space Science and Applications, MS D466, Los Alamos National Laboratory, Los Alamos, NM 87545, USA

ABSTRACT
In the set of 236 GRB afterglows observed by Swift between January 2005 and March 2007, we identify 30 X-ray light-curves whose power-law fall-off exhibit a steepening ("break") at 0.1–10 day after trigger, to a decay steeper than $t^{-1.5}$. For most of these afterglows, the X-ray spectral slope and the decay indices before and after the break can be accommodated by the standard jet model although a different origin of the breaks cannot be ruled out. In addition, there are 27 other afterglows whose X-ray light-curves may also exhibit a late break to a steep decay, but the evidence is not that compelling. The X-ray emissions of 38 afterglows decay slower than $t^{-1.5}$ until after 3 day, half of them exhibiting such a slow decay until after 10 day. Therefore, the fraction of well-monitored Swift afterglows with potential jet-breaks is around 60 percent, whether we count only the strongest cases for each type or all of them. This fraction is comparable to the 75 percent of pre-Swift afterglows whose optical light-curves displayed similar breaks at ~ 1 day. The properties of the prompt emission of Swift afterglows with light-curve breaks show the same correlations (peak energy of GRB spectrum with the burst isotropic output and with burst collimated output) as previously found for pre-Swift optical afterglows with light-curve breaks (the Amati and Ghirlanda relations, respectively). However, we find that Ghirlanda relation is largely a consequence of Amati's and that the use of the jet-break time leads to a stronger Ghirlanda correlation only when the few outliers to the Amati relation are included.

Key words: gamma-rays: bursts - radiation mechanisms: non-thermal - shock waves

1 INTRODUCTION

Observations of Gamma-Ray Burst (GRB) afterglows from 1999 to 2005 have evidenced the existence of breaks in the optical light-curve of many afterglows, occurring at 0.3–3 day and being followed by a flux decay $F_o \propto t^{-\alpha}$, with the index α ranging from 1.3 to 2.8. These breaks have been widely interpreted as due to the tight collimation of GRB outflows: when the jet Lorentz factor decreases below the inverse of the jet half-opening (i.e. when the cone of relativistically beamed emission is wider than the jet), the observer "sees" the jet boundary, which leads to a faster decay of the afterglow flux (synchrotron emission from the ambient medium shocked by the blast-wave). This decay may be further "accelerated" by the lateral spreading of the jet (Rhoads 1999).

The temporal–spectral properties of the afterglow optical emission are roughly consistent with the expectations of the standard jet model, if it assumed that (*i*) the shock microphysical parameters and blast-wave kinetic energy are constant, and (*ii*) the blast-wave kinetic energy per solid angle is the same along any direction This consistency yielded support to the jet interpretation for the optical light-curve breaks. Nevertheless, the basic confirmation of the jet model through observations of achromatic breaks (i.e. exhibited by light-curves at different frequencies) lacked because of the limited coverage in the X-rays. To a large extent, because of the sparser optical follow-up, that proof is still modest today, despite the good X-ray monitoring of GRB afterglows provided by Swift.

Collimation of GRB outflow is a desirable feature to decrease the burst output, as the largest isotropic-equivalent energy release approaches the equivalent of a solar mass (GRB 990123 – Kulkarni et al 1999). From the light-curve break epoch of ~ 1 day, it follows that the half-opening θ_{jet} of GRB jets is of few/several degrees, for which the GRB output is reduced to $\lesssim 10^{51}$ erg (e.g. Frail et al 2001, Panaitescu & Kumar 2001). However, such a tight collimation of the GRB outflow is more than necessary on energetic grounds, as the accretion of the debris torus formed during the collapse of a massive star (the origin of long-duration bursts – e.g. Woosley 1993, Paczyński 1998) or of the black-hole spin can power relativistic jets with more than 10^{52} erg (e.g. Mészáros, Rees & Wijers 1999, Narayan, Piran & Kumar 2001). In other words, without demanding too much energy, GRB jets can be wider than several degrees, placing the afterglow jet-break epoch (which scales as $\theta_{jet}^{8/3}$ for a homogeneous circumburst medium and as θ_{jet}^4 for a wind-like medium) later than usually reachable by afterglows observations.

Recently, Burrows & Racusin (2007) have suggested that Swift X-ray afterglows do not display ~ 1 day breaks as often as pre-Swift optical afterglows. The purpose of this ar-

ticle is (i) to identify the afterglows observed by Swift from January 2005 through March 2007 whose X-ray light-curves steepen to a decay faster than $t^{-1.5}$ (which is, roughly, the lower limit of the post-break decay indices of pre-Swift optical afterglows – figure 2 of Zeh, Klose & Kann 2006), (ii) to find the Swift X-ray afterglows that were monitored longer than a few days and displayed a decay slower than $t^{-1.5}$ (indicating a jet-break occurring well after 1 day), and (iii) to compare the fraction of Swift X-ray afterglows with potential jet-breaks to that of pre-Swift optical afterglows with such breaks. In addition, the temporal–spectral properties of the X-ray afterglows will be used to identify, on case-by-case basis, the required features of the standard jet model.

2 LATE BREAKS IN X-RAY AFTERGLOW LIGHT-CURVES

Figures 1, 2, and 3 display all afterglows observed by Swift until April 2007 with good evidence for a late, 0.1–10 day break, followed to a decay steeper than $t^{-1.5}$. Their pre and post-break indices (α_3 and α_4) of the power-law X-ray light-curve ($C_{0.3-10\,\mathrm{keV}} \propto t^{-\alpha}$) and the slope β of the power-law X-ray continuum (spectral distribution of energetic flux $F_\nu \propto \nu^{-\beta}$) are listed in Table 1. The decay indices were obtained by fitting the 0.3–10 keV count-rate light-curves of Evans et al (2007); the spectral slopes were obtained through power-law fits in the 1–5 keV range to the specific count-rates $C_\nu \propto \nu^{-(\beta+1)}$ of Butler & Kocevski (2007).

Figure 4 compares the decay indices and spectral slopes of these 30 afterglows with the $\alpha - \beta$ relations expected for the synchrotron emission from the forward-shock (the standard jet model), assuming that the circumburst medium is either homogeneous or has the r^{-2} radial stratification expected for the wind of a massive stellar GRB progenitor. The models that reconcile the observed α and β are listed in Table 1. Derivations of these relations for a spherical outflow and for a spreading jet can be found in Mészáros & Rees (1997), Sari, Piran & Narayan (1998), Chevalier & Li (1999), Rhoads (1999), Sari, Piran & Halpern (1999), Panaitescu & Kumar (2000).

For the post jet-break emission, we also consider the case of a conical jet which does not undergo significant spreading, as could happen if the jet edge is not too sharp (Kumar & Granot 2003), but surrounded by an envelope which prevents its lateral expansion. In this case, the post-break decay index α_4 is larger by 3/4 (1/2) than the pre-break index α_3 for a homogeneous (wind-like) medium (Panaitescu, Mészáros & Rees 1998), this increase resulting from that, after the jet-break, the number of emitting electrons within the "visible" region of angular extent equal to the inverse of the jet Lorentz factor stops increasing (as the jet is decelerated) because the outflow opening is less than that of the cone of relativistic beaming. Lateral spreading of the jet, if it occurs, enhances the jet deceleration and yields an extra contribution to the jet-break steepening $\alpha_4 - \alpha_3$ which is smaller than the 3/4 (1/2) resulting from the "geometrical" effect described above.

As can be seen from Figure 4 and Table 1, most pre-break X-ray decays require either that the cooling frequency (ν_c is below X-rays (model S1), in which case α_3 is independent of the ambient medium stratification, or that the medium is homogeneous and ν_c is above X-rays (model S2a). For six afterglows, the pre-break decay is too slow to be explained by the standard forward-shock model, indicating a departure from its assumptions. Most likely, this departure is the increase of the shock's energy caused by the arrival of fresh ejecta (Paczyński 1998, Rees & Mészáros 1998, Panaitescu, Mészáros & Rees 1998, Nousek et al 2006, Panaitescu et al 2006, Zhang et al 2006). If the post-break decays of these six afterglows are attributed to a jet whose boundary is already visible then the jet-break time should be before the epoch when energy injection ceases so that, shortly after energy injection stops being dynamically important, the jet Lorentz factor falls below the inverse of the jet opening.

Alternatively, the X-ray light-curve breaks of the six af-

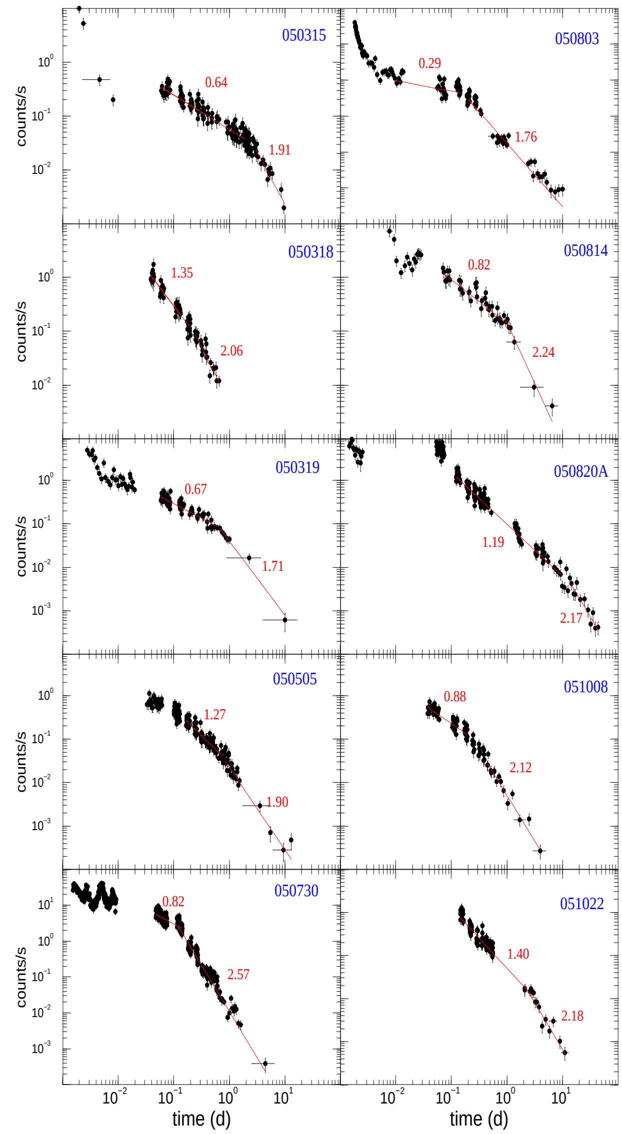

Figure 1. Ten Swift afterglows whose X-ray light-curves exhibit a break at 0.1–10 d to a post-break decay faster than $t^{-1.5}$. These steepenings could be jet-breaks resulting from the boundary of the GRB outflow becoming visible to the observer. Power-law fits ($C_{0.3-10\,\mathrm{keV}} \propto t^{-\alpha}$) and the exponents α are shown (standard deviations given in Table 1).

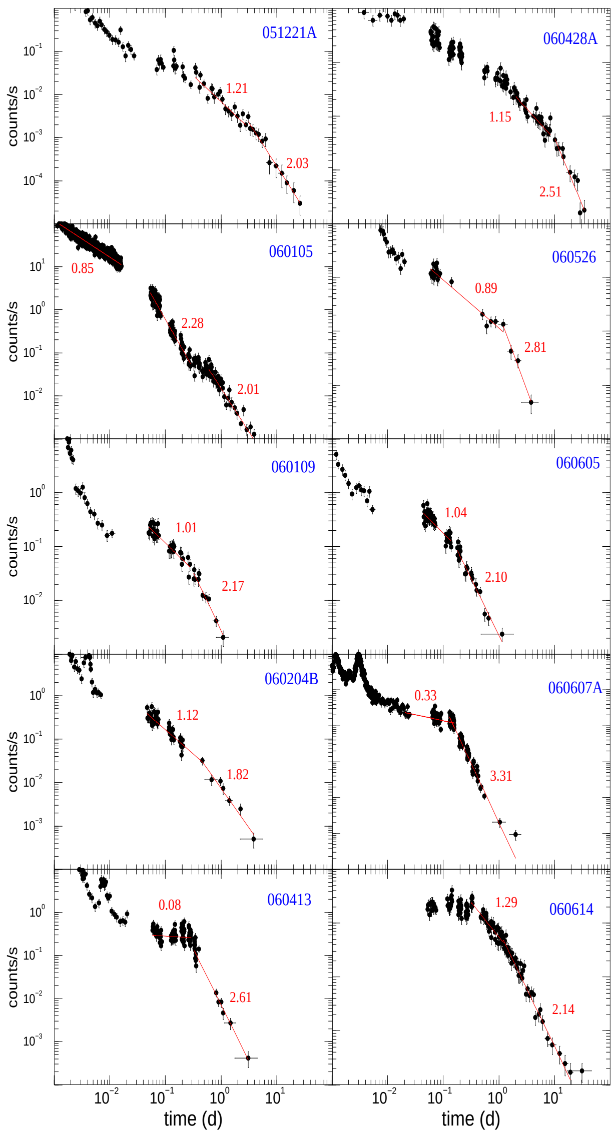

Figure 2. As in Figure 1, for another 10 Swift afterglows.

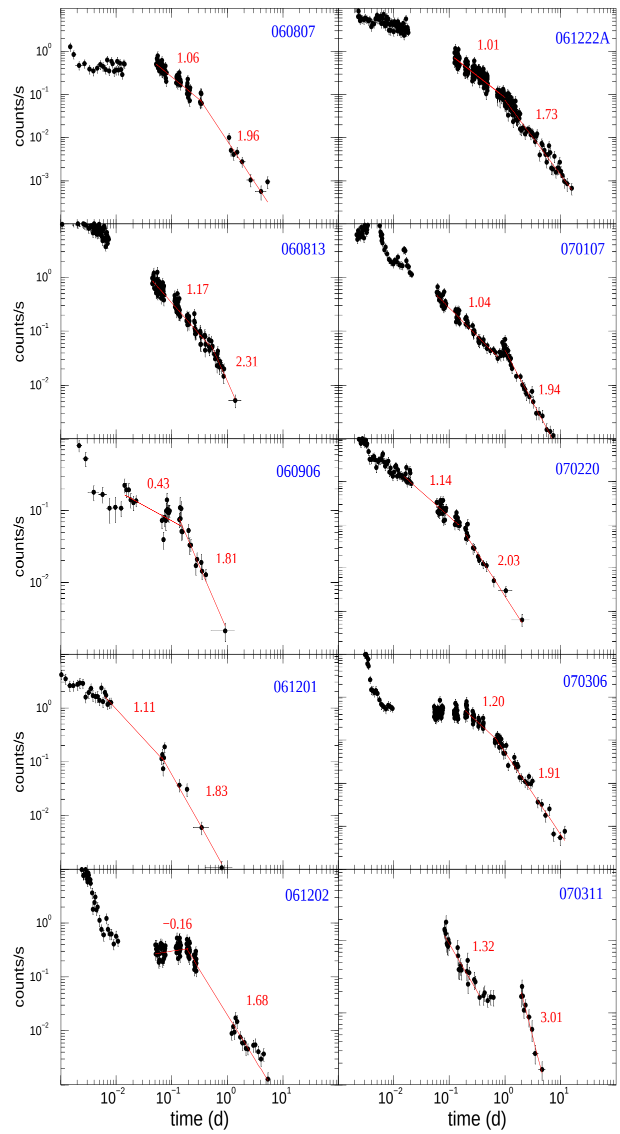

Figure 3. Last set of 10 Swift afterglows with jet-breaks.

terglows with slow pre-break decays could be attributed to the end of energy injection into a spherical (or wide opening) blast-wave. As shown in the lower panel of Figure 4, the post-break decays of four of these six afterglows are consistent with the S2a model (ν_c above X-ray, homogeneous medium); still, two afterglows (GRBs 060413 and 060607A) exhibit a post-break decay that is too steep for any "S" model.

Attributing X-ray light-curve breaks to cessation of energy injection can be extended to other afterglows: for the measured spectral slope β, the post-break decays of 19 afterglows are consistent within 1σ with that expected for a spherical outflow ("S" models in the lower panel of Figure 4). Here, consistency within 1σ between a model expectation $\alpha_{model}(\beta) = a\beta + b$ and an observed index α_{obs} is defined by $\alpha_{obs} - \alpha_{model}$ being within $(\sigma_\alpha^2 + a^2\sigma_\beta^2)^{1/2}$ of zero, where σ_α and σ_β are the 1σ standard deviations given in Table 1.

Thus only 11 afterglows have a post-break decay that is too fast for a spherical outflow and require a jet-interpretation for the break. However, it seems unlikely that cessation of energy injection can be so often the source of X-ray light-curve breaks, for the following reason. A similar analysis of the optical decay indices and spectral slopes done for 10 pre-Swift afterglows with optical light-curve breaks indicated that six of those breaks are consistent with arising from an episode of energy injection into a spherical blast-wave, ending at the break epoch (Panaitescu 2005a). Nevertheless, the numerical modelling of the radio, optical, and X-ray emission of those six afterglows has shown that the broadband emission of only two of them can be accommodated by energy injection (Panaitescu 2005b), the primary reason for the failure of this model being that the radio emission from the ejecta electrons that were accelerated by the reverse shock is too bright.

Therefore, while it is possible that up to 2/3 of the Swift X-ray breaks listed in Table 1 arise from cessation of energy injection, this interpretation does not find much support in the light-curve breaks of pre-Swift afterglows. For this reason, we propose that the 30 Swift X-ray breaks of Table 1 are due to the GRB outflow being narrowly collimated, al-

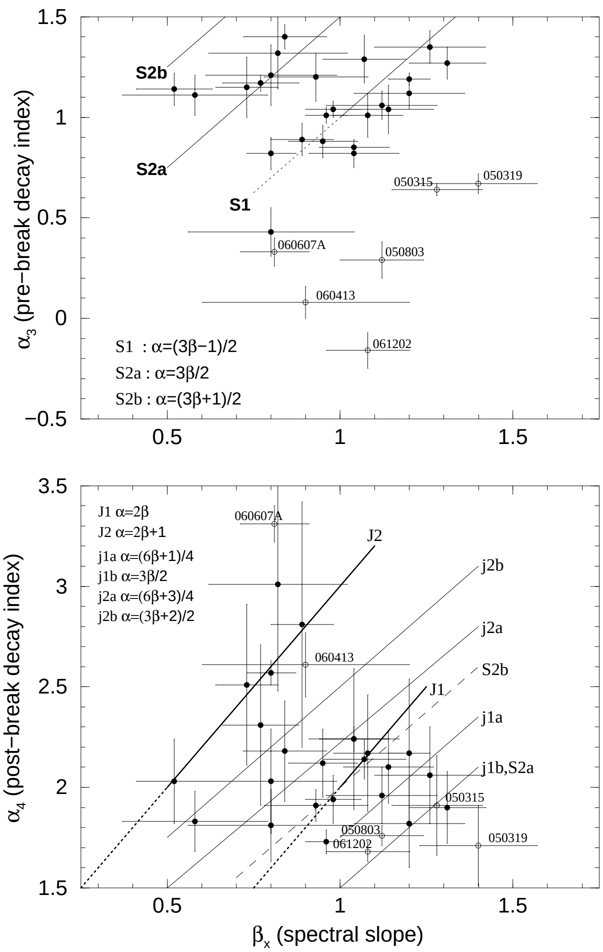

Figure 4. X-ray spectral slope vs. pre-break (upper panel) and post-break (lower panel) decay index for the 30 Swift afterglows with jet-breaks shown in Figures 1, 2 and 3. Also shown are the model expectations for the forward-shock synchrotron emission. Model labels are as following: "S" = outflow opening wider than the inverse of its Lorentz factor (i.e. a spherical outflow or a jet observed before the jet-break time), "J" and "j" = laterally-spreading and conical jet, respectively, observed after the jet-break time, "1" = cooling frequency (ν_c) below X-ray, "2" = ν_c above X-ray, "a" = homogeneous medium, "b" = wind-like medium. For "J" and "1" models, the decay index is independent of the radial structure of the ambient medium. Upper panel: six afterglows (labelled) have pre-break decays that are too slow to be explained by the standard forward-shock model. Lower panel: one afterglow (060607A) decays too fast after the break to be accommodated by the jet model.

though a different origin cannot be ruled out based only on X-ray observations.

Last column of Table 1 lists the combination of models for the pre- and post-break decays that explains both phases in a self-consistent manner, the type of medium and location of cooling frequency being the same both before and after the break. The features of those "global" afterglow models show that: (*i*) the cooling frequency must be below X-rays ("1" models) for 2/3 of afterglows, (*ii*) 1/4 of afterglows require a homogeneous medium ("a" models), (*iii*) 1/10 require a wind medium ("b" models), (*iv*) 1/3 of afterglows require a spreading jet ("J" models), and (*v*) 1/3 require a conical jet ("j" models), larger fractions allowing any of the above features as they are not always well constrained. This shows that there is a substantial diversity in the details of the forward-shock model that accommodate the temporal and spectral properties of Swift X-ray afterglows.

3 SWIFT X-RAY AND PRE-SWIFT OPTICAL BREAKS

In the Jan05–Mar07 set of Swift afterglows, we find another 27 potential jet-breaks at 0.1–10 d, followed by a $t^{-1.5}$ decay or steeper: GRB 050401, 050408, 050525A, 050603, 050712, 050713A, 050713B, 050726, 050802, 050826, 050922B, 051001, 051016B, 051211B, 060121, 060124, 060210, 060218, 060219, 060306, 060707, 060719, 060923C, 061019, 061126, 070125, 070318. For some of these afterglows, the post-break decay was followed for only 0.5 dex in time, for others, the break is only marginally significant, with the break magnitude ($\alpha_4 - \alpha_3$) being smaller than for the 30 afterglows in Table 1. Therefore, in the Jan05–Mar07 set of X-ray afterglows, there could be as many as 57 with jet-breaks. However, we cannot exclude the possibility that some of those light-curve breaks arise from another mechanism, such as the sudden change of energy injected in the forward shock.

In the same sample, there are 18 afterglows (GRB 050607, 050915B, 051016A, 060108, 060111A, 060115, 060123, 060510A, 060604, 060708, 060712, 060904A, 060912A, 060923A, 061110A, 070223, 070224, 070328) exhibiting a $t^{-1.5}$ decay or slower until 3–10 day, indicating that their jet-breaks occurred after the last observation. Similar decays, but lasting until 10–30 day, are displayed by 13 afterglows (GRB 050716, 050824, 051021A, 051109A, 051117A, 060202, 060714, 060814, 061007, 061121, 061122, 070110, 070129) and by 6 afterglows (GRB 050416A, 050822, 060206, 060319, 060729, 061021) until after 30 day. Thus, the number of well-monitored afterglows without a jet-break is 19, but could be as high as 37 if all the other 18 light-curves followed for less than 10 day are included.

For the remaining more than 100 afterglows the temporal coverage is insufficient to test for the existence of jet-breaks. We conclude that, if only the afterglows with good evidence for existence or lack of jet-breaks are counted, then the fraction of Swift afterglows with jet-breaks is 30/(30+18)=0.63; if we include all potential cases for each type then that fraction is 57/(57+37)=0.61.

In pre-Swift afterglow observations, evidence for light-curve breaks is found only in the optical emission. The X-ray coverage of pre-Swift afterglows at the time of the optical break is too limited to test for the existence of a simultaneous break in the X-ray emission. The radio light-curves of a dozen pre-Swift afterglows show breaks at 1–10 day, however the pre and post-break decays indicate that those breaks arose from the passage of the synchrotron peak frequency through the radio. All radio post-break decays are slower than $t^{-1.5}$, hence a jet origin for those breaks is very unlikely.

There are 12 pre-Swift optical afterglows with good evidence for a break at 0.3–3 day to a decay steeper than $t^{-1.5}$: GRB 980519, 990123, 990510, 991216, 000301C, 000926, 011211, 030226, 030328, 030329, 030429, 041006 (figure 1 of Zeh, Klose & Kann 2006). Three afterglows (GRB 011121,

Table 1. Decay indices (α_3 before break, α_4 after break), spectral slopes (β_x, stars indicate values taken from Willingale et al 2007), break epoch (t_b), and possible models for the 30 Swift X-ray afterglows with jet-breaks. Models consistent with the observations at the $1\sigma - 2\sigma$ level are given in round parentheses only when no model is consistent within 1σ with the observed α and β. Model coding is given in captions of Figure 4. "ei" is for energy injection during the pre-break phase. "$\nu_c = \nu_x$" is for cooling frequency crossing the X-ray around the jet-break time.

GRB	α_3(sd)	β_x(sd)	α_4(sd)	Pre-break	t_b(day)	Post-break Model	Global	Model	
050315	0.64(.03)	1.28(.13)	1.91(.25)	ei	3	j1a, j1b	S1+ei	$\longrightarrow$	j1a/j1b
050318	1.35(.08)	1.26(.16)	2.06(.24)	S1	0.3	j1a, j1b	S1	$\longrightarrow$	j1a/j1b
050319	0.67(.05)	1.40(.17)	1.71(.20)	ei	0.7	(j1a), (j1b)	S1+ei	$\longrightarrow$	(j1a)/(j1b)
050505	1.27(.08)	1.31(.11)	1.90(.18)	(S1)	0.8	j1b	(S1)	$\longrightarrow$	j1b
050730	0.82(.08)	0.80(.07)	2.57(.06)	S1	0.15	J2	S1	$\nu_x = \nu_c$	J2
050803	0.29(.09)	1.12(.12)	1.76(.05)	ei	0.15	j1a, j1b	S1+ei	$\longrightarrow$	j1a/j1b
050814	0.81(.07)	1.04(.13)	2.24(.35)	(S1)	1	J1, j2a, j2b	(S1)	$\longrightarrow$	J1
050820A	1.19(.03)	1.20(.06)	2.17(.37)	(S1)	10	J1, j1a, j1b, j2a	(S1)	$\longrightarrow$	J1/j1a/j1b
051008	0.88(.08)	0.95(.10)	2.12(.17)	S1	0.25	J1, j2a	S1	$\longrightarrow$	J1
051022	1.40(.06)	0.84(.12)	2.18(.25)	S2a	3	j2a, j2b	S2a	$\longrightarrow$	j2a
051221A	1.21(.15)	0.80(.19)	2.03(.26)	S2a	3	J1, j2a, j2b	S2a	$\longrightarrow$	j2a
060105	0.85(.01)	1.04(.10)	2.24(.06)	(S1)	0.025/0.6	J1, j2a	(S1)	$\longrightarrow$	J1
060109	1.01(.11)	1.08(.10)*	2.17(.29)	S1	0.4	J1, j1a, j2a	S1	$\longrightarrow$	J1/j1a
060204B	1.12(.08)	1.20(.16)	1.82(.22)	S1	0.5	j1a, j1b	S1	$\longrightarrow$	j1a
060413	0.08(.08)	0.9(.3)*	2.61(.16)	ei	0.3	J2, j2b	S2a/b+ei	$\longrightarrow$	J2b
...	...	...	...	...	...	...	S2b+ei	$\longrightarrow$	j2b
060428A	1.15(.15)	0.73(.09)	2.51(.40)	S2a	10	J2, j2b	S2a	$\longrightarrow$	J2
060526	0.89(.08)	0.87(.06)*	0.89(.09)	S1	1.5	J2, j2b	S1	$\nu_x = \nu_c$	J2
060605	1.04(.12)	1.14(.13)	2.10(.18)	S1	0.15	J1, j1a	S1	$\longrightarrow$	J1/j1a
060607A	0.33(.07)	0.81(.10)	3.31(.09)	ei	0.15	???		???	
060614	1.29(.12)	1.07(.12)	2.14(.10)	S1	1.5	J1	S1	$\longrightarrow$	J1
060807	1.06(.07)	1.12(.16)	1.96(.14)	S1	0.3	J1, j1a	S1	$\longrightarrow$	J1/j1a
060813	1.17(.04)	0.77(.11)	2.31(.40)	S2a	0.5	J2, j2a, j2b	S2a	$\longrightarrow$	J2/j2a
060906	0.43(.12)	0.80(.24)	1.81(.18)	S1	0.2	J1, j1a, j2a, j2b	S1	$\longrightarrow$	J1/j1a
061201	1.11(.10)	0.58(.21)	1.83(.15)	S2a/S2b	$\lesssim 0.08$	J2, j2a, j2b	S2a	$\longrightarrow$	J2/j2a
...	...	...	...	...	...	...	S2b	$\longrightarrow$	j2b
061202	-0.16(.09)	1.08(.12)	1.68(.05)	ei	0.2	j1b	S1+ei	$\longrightarrow$	j1b
061222A	1.01(.04)	0.96(.06)	1.73(.06)	S1	1	j1a	S1	$\longrightarrow$	j1a
070107	1.04(.04)	0.98(.08)	1.94(.12)	S1	1	J1	S1	$\longrightarrow$	J1
070220	1.14(.08)	0.52(.11)	2.03(.21)	S2b	0.2	J2, j2b	S2b	$\longrightarrow$	J2/j2b
070306	1.20(.12)	0.93(.15)	1.91(.08)	S2a	0.7	J1, j2a	S2a	$\longrightarrow$	j2a
070311	1.32(.18)	0.82(.20)	3.01(.53)	S2a	1–2	J2	S2a	$\longrightarrow$	J2

020124, 020405) may also had a break, though the evidence is not so strong. A break to a decay slightly less steep than $t^{-1.5}$ was observed for three afterglows (GRB 010222, 020813, 021004). We find only 5 optical afterglows followed for more than several days that have a decay slower than $t^{-1.5}$: GRB 970228, 970508, 980329, 000418, 030323. Therefore the fraction of well-monitored optical afterglows with potential jet-breaks is 12/(12+5)=0.71 if only the best cases for light-curve breaks are taken into account and 18/(18+5)=0.78 including the other 6 potential optical breaks.

Therefore the fraction of Swift X-ray afterglows with light-curve breaks at 0.1–10 day (60 percent) is slightly smaller than that of pre-Swift optical afterglows with breaks at 0.3–3 day (75 percent).

4 AMATI AND GHIRLANDA RELATIONS

Having identified new breaks in afterglow light-curves that may qualify as jet-breaks, we calculate the jet opening from the break epoch t_b, assuming a GRB efficiency of 50 percent and a homogeneous circumburst medium of particle density $n = 1$ cm^{-3}. From there, the GRB collimated output is

$$E_{jet} = 1.9 \times 10^{50} \left(\frac{E_\gamma}{10^{53}\,\mathrm{erg}} \frac{t_{b,d}}{z+1} \right)^{3/4} \mathrm{erg}\ , \qquad (1)$$

where E_γ is the burst isotropic-equivalent output in the (host-frame) 1 keV–10 MeV range, $t_{b,d}$ is the jet-break epoch measured in days, and numerical coefficient is for the arrival-time of photons emitted from the jet edge. The results below do not change much if a wind-like medium is assumed, for which $E_{jet} \propto (E_\gamma t_b)^{1/2}$, because we shall use $\log E_{jet}$ in the calculation of the correlation coefficient r and changing the multiplying factor (3/4 to 1/2) of $\log E_{jet}$ does not affect r (though it would alter the slope of the best-fits involving $\log E_{jet}$).

The necessary information (low and high-energy burst spectral slopes, peak energy E_p of the νF_ν GRB spectrum, burst fluence and redshift) to study the Amati and Ghirlanda relations (most recently presented by Amati 2006 and Ghirlanda et al 2007) between the intrinsic peak energy $E'_p = (z+1)E_p$ of the burst spectrum and the isotropic GRB output E_γ or the collimated GRB energy E_{jet} is available for

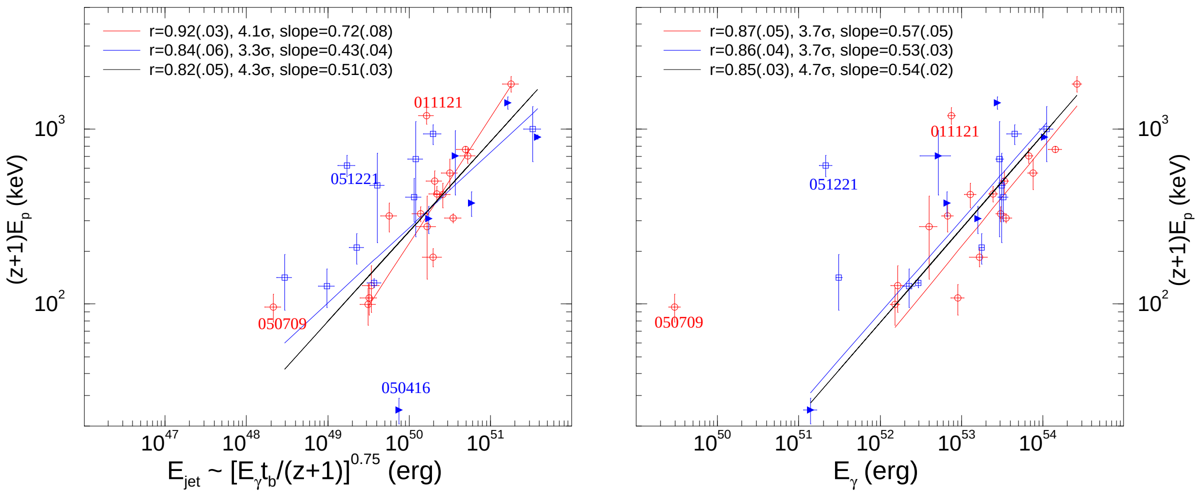

Figure 5. Correlation of host-frame peak energy of the νF_ν GRB spectrum and k-corrected 1 keV–10 MeV collimated GRB output (Ghirlanda relation – left panel) and isotropic-equivalent GRB energy release (Amati relation – right panel) for 15 pre-Swift afterglows with optical light-curve jet-breaks (red symbols, fit shown with red line), 9 Swift afterglows with X-ray jet-breaks (blue squares) and 6 without (blue triangles) (fit shown with dashed line), and for the entire set of 30 afterglows (black line). Labelled afterglows are not included. Legends give the linear-correlation coefficient r of plotted quantities in log-log space, significance level for that correlation, and slope of linear best-fit, all accounting for sample variance.

(i) 15 pre-Swift optical afterglows: GRB 990123, 990510, 991216, 000926, 010222, 011121, 020124, 020405, 020813, 021004, 030226, 030328, 030329, 030429, 041006

(ii) 9 of the 57 Swift X-ray afterglows with good or potential evidence for jet-breaks: GRB 050318, 050505, 050525A, 050803, 050814, 050820A, 060124, 060605, 060906

(iii) 6 of the 37 Swift X-ray afterglows without a jet-break until at least 3 day: GRB 050416A, 051109A,060115, 060206, 061007, 061121

(iv) 2 short-bursts (lasting less than 2 seconds): GRB 050709 and 051221A.

Figure 5 displays the significance of the Amati and Ghirlanda correlations for the set 15 pre-Swift afterglows with optical jet-breaks, 15 Swift afterglows with X-ray jet-breaks or without one until more than 3 day, and the joint set of 30 afterglows. The long-duration GRB 011121 and the only two short-bursts 051221A and 050709 were excluded as they are outliers for the Amati relation. For the Ghirlanda relation, GRB 050416A was excluded as an outlier and the last observation epoch of the 6 X-ray afterglows without jet-breaks were taken as jet-break times. Their true jet-break epochs would evidently be later which, as can be seen from Figure 5, would weaken the Ghirlanda relation (see also figure 6 of Sato etal 2007 and figure 9 of Willingale et al 2007).

The linear correlation coefficients and best-fit slopes given in Figure 5 show that:

(i) Swift X-ray afterglows display the same Amati correlation as the pre-Swift optical afterglows but a weaker Ghirlanda correlation,

(ii) the addition of Swift afterglows weakens the Ghirlanda correlation (smaller correlation coefficient) and increases the statistical significance of the Amati correlation. The former result was also pointed out by Campana et al (2007), but we note that half of the 8 X-ray light-curve breaks identified in that work are followed by decays slower than $t^{-1.5}$ and, thus, they may not be jet-breaks,

(iii) going from isotropic to collimated GRB output brings the three outlying bursts for the Amati relation closer to the rest.

For the entire set of 30 afterglows with optical and/or X-ray light-curve jet-breaks, we find a the log-log space slope for the Amati relation ($s_A = 0.54 \pm 0.02$) which is consistent with that obtained by Amati (2006) for 41 afterglows ($s_A = 0.49 \pm 0.06$), but a smaller one for the Ghirlanda relation ($s_G = 0.51 \pm 0.03$) than that obtained by Ghirlanda et al (2007) for 25 afterglows ($s_G = 0.70 \pm 0.04$). This discrepancy is due to that we did not include here the afterglows of Ghirlanda (2007) that have breaks followed by decays shallower than $t^{-1.5}$, which are unlikely to be jet-breaks, and have used a larger set of Swift afterglows.

That the $E'_p - E_{jet}$ correlation coefficient ($r_G = 0.82 \pm 0.05$) is nearly the same as for $E'_p - E_\gamma$ ($r_A = 0.85 \pm 0.03$) indicates that the addition of a new observable (the jet-break time t_b) does not reduce the spread of the Amati relation. This suggests that the jet-break time is not correlated with either burst observable. Indeed, we find such correlations not to be statistically significant: $r(\log E'_p, \log t'_b) = 0.25 \pm 0.10$ and $r(\log E_\gamma, \log t'_b) = 0.14 \pm 0.05$, where $t'_b = t_b/(z+1)$ is the host-frame jet-break time.

For the 15 pre-Swift afterglows with optical breaks, the slope of the $E'_p - E_{jet}$ best-fit ($s_G = 0.72 \pm 0.08$) is equal to that of the $E'_p - E_\gamma$ best-fit ($s_A = 0.57 \pm 0.05$) multiplied by $\mathrm{d}\log \mathrm{E}_\gamma / \mathrm{d}\log \mathrm{E_{jet}} = 4/3$ (from equation (1). This indicates that the Ghirlanda relation for pre-Swift afterglows is the consequence of Amati's. For the entire set of 30 afterglows, $s_G < (4/3)s_A$, consistent with the same conclusion.

5 CONCLUSIONS

Summarizing our findings, out of the more than 200 X-ray afterglows monitored by Swift from January 2005 through March 2007, about 100 have been followed sufficiently long

to test for the existence of late light-curve steepenings. About 60 percent of these well-monitored afterglows display a clear or a possible X-ray light-curve break at 0.1–10 day followed by a $t^{-1.5}$ or steeper decay. These are potential jet-breaks, resulting when the jet Lorentz factor decreases below the inverse of the jet opening. However, from X-ray observations alone, we cannot exclude other origins for the light-curve breaks.

More stringent tests of the jet model for X-ray light-curve breaks require a good optical coverage. So far, only a couple of the 30 X-ray breaks listed in Table 1 were followed in the optical, showing that the X-ray breaks were achromatic, as expected for a jet origin: GRB 050730 (Pandey et al 2006, Perry et al 2007), GRB 060124 (Curran et al 2007), and GRB 050526 (Dai et al 2007). For the last two, the pre- and post-break optical and X-ray decay indices are consistent with the jet interpretation but, for the first, the post-break optical light-curve falls-off too slowly ($F_o \propto t^{-1.4\pm0.2}$) compared to the X-ray emission ($F_o \propto t^{-2.6\pm0.1}$).

Around 75 percent of the pre-Swift optical afterglows with a good coverage exhibit a light-curve break at 0.3–3 day. Hence the fraction of Swift X-ray afterglows with breaks is slightly smaller, but comparable, to that of pre-Swift optical afterglows.

The burst and redshift information necessary to test the Ghirlanda ($E'_p \propto E_{jet}^{0.7}$, E'_p = peak energy of the burst spectrum, $E_{jet} \propto (E_\gamma t_b)^{3/4}$ = GRB collimated output, E_γ = GRB isotropic energy release, t_b = afterglow break epoch) and Amati ($E'_p \propto E_\gamma^{0.5}$) correlations exist for only eight of the 30 afterglows with X-ray jet-breaks. These afterglows display the mentioned correlations at the $\gtrsim 2\sigma$ level. Adding them to a set of 15 pre-Swift afterglows with optical light-curve breaks, leads to correlations which are significant at the $\sim 4\sigma$ level. However, including the jet-break time in the Amati correlation does not lead to a stronger (Ghirlanda) correlation, unless the few under-energetic outliers shown in Figure 5 are taken into account. Furthermore, because the jet-break time is not correlated with either burst property, the slope of the $\log E'_p - \log E_{jet}$ best-fit is that expected from the slope of $\log E'_p - \log E_\gamma$ fit. These two facts indicate that the Ghirlanda correlation results almost entirely from the Amati correlation.

For the cosmological use of GRBs, one is interested in obtaining a good calibrator of the source luminosity E_γ with other burst observables, a quality which is quantified by the linear correlation coefficient. Although the Ghirlanda correlation is stronger than Amati's when outliers are included, the Ghirlanda relation is not necessarily better for constraining cosmological parameters because outliers to the Amati relation, such as the three underluminous bursts shown in Figure 5, should stand out and be easily to excise from the Hubble diagram constructed based on the Amati relation (i.e. with the luminosity distance inferred from the burst isotropic luminosity obtained from the peak energy of the burst spectrum). As shown in §4, if we consider only bursts which are not outliers to the Amati relation, the addition of a new observable (the afterglow jet-break epoch) does not yield a stronger correlation than that of Amati's. Thus, with the current sample of afterglows with jet-breaks, we suggest that the Amati relation should be at least as useful for constraining cosmological parameters as is the Ghirlanda relation (Ghirlanda et al 2004, Schaefer 2007).

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